ENERGY CONVERSION SYSTEMS

HARRY A. SORENSEN

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Harry A. Sorensen

Washington State University

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PREFACE

From the study of thermodynamics, fluid mechanics, and heat transfer, the engineering student acquires the basic concepts of energy transfer and energy conversion. At this point however, he usually has only limited comprehension of the physical systems in which the conversion of energy is accomplished. The need to enhance the student's understanding of energy conversion systems becomes clear in the light of the concentrated effort currently directed to conservation of energy and development of nonconventional energy sources.

This text was prepared with the expectation of achieving a comprehensive treatment of the systems, both conventional and nonconventional, that convert primary forms of energy into usable mechanical and electrical energy. The operating principles of the energy conversion system are established, and an examination of the design and construction of the equipment serves as a means to relating the theoretical concepts to the physical system. Finally, the utility of the energy conversion system is investigated in the light of the performance, operating difficulties, and particularly the anticipated operating economy.

The introductory chapter on power generation precedes the chapter that deals with commercial fuels. Power generation systems are presently highly dependent upon the consumption of fossil and nuclear fuels. An understanding of the availability and the physical and chemical characteristics of fuels is important to the selection of the most appropriate fuel for a given system.

A comprehensive treatment of energy conversion must necessarily include an examination of the machines that consume high-level energy. The text thus includes sections that deal with cooling systems and with various machines used for moving and pumping gases and liquids. Large amounts of energy, usually electrical energy, are consumed by these machines, hence their proper selection and operation must necessarily be observed.

Steam engines on a few occasions are used for industrial power applications. Within the past few years, a modest investigation has been directed to the application of the steam engine to highway vehicles. While the steam engine is not likely to regain its former position of importance, it is nevertheless a basic energy converter, and a limited examination of this machine is in order.

A substantial portion of the book relates to internal combustion and gas turbine engines and to fossil fuel-fired and nuclear power plants. These power plants, together with the hydro power plants, produce virtually all the mechanical and electrical energy consumed by the domestic and commercial sectors of the economy. Because these power plants will for many years remain the major power producers, they are examined in considerable detail. Reliability, high performance, and good economy are emphasized, while attention is directed to the restrictions imposed by environmental control regulations.

In the final two chapters, nonconventional energy conversion systems are examined, and potential commercial applications are investigated. The principal problems of low-level performance, low power-producing capability, and poor economy are noted. It is particularly significant to observe whether any of these energy converters might in time serve to alleviate the heavy dependence upon petroleum-based fuels or contribute to an improvement in the environment.

The subject matter included in the text is arranged to allow considerable flexibility in developing a particular course sequence. Various sections and chapters can be omitted without incurring a lack of continuity.

The text material was prepared with the anticipation that the reader is grounded in thermodynamics and fluid mechanics and has some understanding of the basic concepts of heat transfer.

The International System of Units (SI) is employed throughout this text. English units appear occasionally in order to introduce a familiar or commonly used quantity. Some energy resources are reported in English units in order to avoid altering the original reference.

Engineering and scientific publications were important sources of information that contributed to the development of this textbook. Numerous industrial companies and various organizations generously provided illustrations and technical data for which I am most appreciative. I should like to thank the members of the Mechanical Engineering Department at Washington State University for their many helpful suggestions. I am particularly indebted to Richard W. Crain, Jr., who read portions of the manuscript, and to James S. Englund for his contributions to the section on solar energy collection.

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Pullman, Washington ***H.A.S.***

CONTENTS

CHAPTER ONE

INTRODUCTION TO POWER GENERATION

For many years, the inhabitants of the world have had at their disposal abundant sources of energy that could be utilized at low cost in many ways beneficial to mankind. In some respects, energy has been used wastefully, and in the more affluent nations high energy consumption is now judged to be somewhat irresponsible. It has become painfully apparent in the past few years that nonrenewable energy sources are finite and are in danger of depletion, to various degrees, in the not too distant future. Conservation and efficient use of energy must be observed in order to ensure a strong and stable world economy.

Solar and geothermal energy can be used directly for heating. Other energy sources are not directly usable, hence some kind of conversion process must be employed to change the energy to a different form, that is, to one of direct utility. These highly important energy conversion processes produce thermal energy and generate power. An examination of the various energy conversion systems will disclose the economic and practical limitations imposed on their use and indicate the effectiveness that may be anticipated in achieving the energy conversion.

1.1 THE NEED FOR POWER

Industrial development and improvement in our way of life are highly dependent upon an abundant supply of inexpensive energy. A human being is a comparatively feeble power plant. The muscular power of man is about 70 W when working at a normal rate, with higher power ratings possible over short periods of time. Dependence upon labor force alone would place any nation in the class of a most primitive society. Energy may be regarded as a multiplying factor that greatly enhances man's ability to fashion resource materials into useful products and provide a wide variety of essential services.

The total energy consumed annually in a country is a measure of the level of the national economy. Figure 1.1 shows the increase in the total energy consumption that has occurred over the past five to six decades in the United States. The general upward trend in the consumption of energy was interrupted during the depression years of the 1930 decade and in the early years of the 1970 decade, when energy conservation measures were adopted.

The sustained increase in the production of electrical energy in the United States is shown in Fig. 1.2. For several decades, the production of electrical energy has essentially doubled every 10 years. Substantial increases in the consumption of electrical energy have occurred in all sectors of the economy—domestic, commercial, and industrial—and indicate a continuous improvement in the productivity of the nation.

A brief survey is made in this chapter of the various types of power plants as to their development, applications, and probable future status. In later chapters, a detailed examination and analysis is presented for each type of power plant. Today, environmental restrictions influence to a substantial degree the design, location, and operation of virtually all power plants.

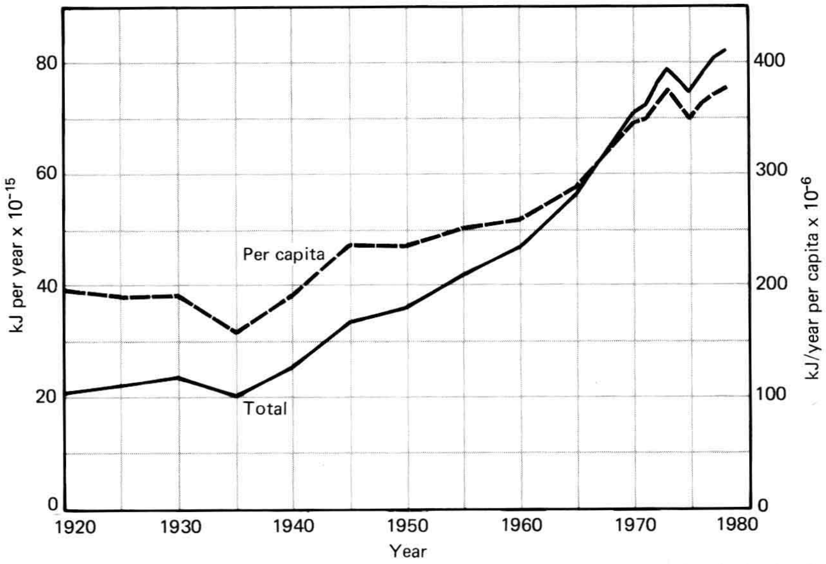

Figure 1.1 Energy consumption in the United States. ***Source:*** Statistical Abstract of the United States, U.S. Dept. of Commerce, Bureau of the Census; and U.S. Dept. of Energy, Electric Power Statistics.

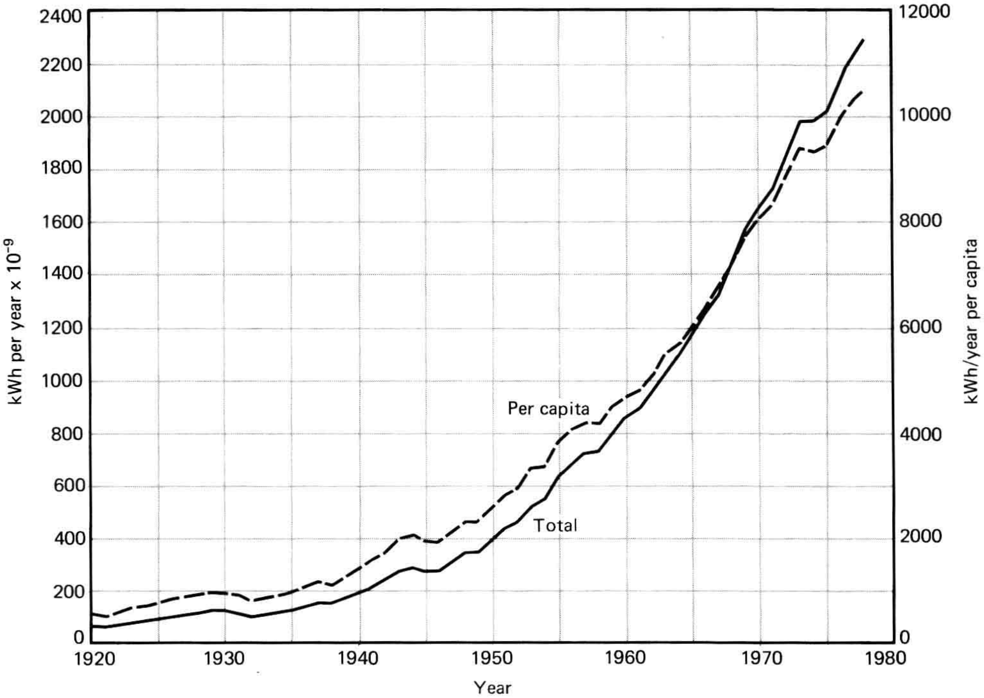

Figure 1.2 Net production of electrical energy in the United States (utility and industrial generating plants). Alaska and Hawaii included in 1959 and subsequent years. ***Source:*** Historical Statistics of the United States, Colonial Times to 1970; U.S. Dept. of Commerce, Bureau of the Census; and the U.S. Dept. of Energy, Electrical Power Statistics.

The survey will cover mainly the power systems that have acquired commercial status. Later sections of the text will explore possible applications of other energy conversion devices presently on test or under development.

Table 1.1 presents a classification of energy conversion systems used in power production. A small number of systems of minor importance are not included in Table 1.1. For some of the systems, a subdivision would be employed to designate a fossil or nuclear fuel or other source of energy.

TABLE 1.1 Power Generation Systems

- **I** Thermal
  - **(a)** Steam (vapor) power plants
    - **1** Reciprocating engine
    - **2** Turbine
  - **(b)** Internal combustion engine—reciprocating
  - **(c)** External combustion engine—reciprocating
  - **(d)** Gas turbine engine
- **II** Hydroelectric
  - **(a)** Water source: rivers
  - **(b)** Water source: tides
- **III** Wind
- **IV** Direct energy conversion
  - **(a)** Fuel cell (chemical)
  - **(b)** Photovoltaic
  - **(c)** Thermal
    - **1** Magnetohydrodynamic
    - **2** Thermionic
    - **3** Thermoelectric

In general, commercial- and industrial-type power plants are designed and operated so as to conform to the economic principle of achieving an acceptable return on the investment. Stated somewhat differently, the total cost, that is, the capital and operating costs, for producing power should be in a competitive range.

Economy however may not be the primary consideration for power plants constructed for special applications. For example, a power plant installed in a space vehicle is required to meet certain criteria that are paramount to economy.

1.2 WIND POWER

Currently, the amount of power produced by wind is negligible. The first power plants developed by man were relatively feeble water wheels and windmills that utilized the naturally occurring sources of energy available in moving masses of water and wind. Early applications of these energy conversion machines were for grinding grain and pumping water. As might be expected, there are only incomplete records of these early power developments, since they were constructed so many years ago. Despite worldwide use of wind power plants throughout many centuries, the development of these machines was generally of limited scope and confined to low-output installations.

The operating principle of the windmill is comparatively simple, and workable designs have resulted from trial-and-error procedures. Application of engineering concepts, including aerodynamic theory, to the design of wind power plants will however improve the performance of the machines. Air undergoes a change in momentum as it flows across the rotor vanes. The resulting force acting on the vanes causes the rotor to turn against an external, resisting torque. Work is performed on the rotor at the expense of the kinetic energy in the moving air.

In 1941, a wind turbine-generator rated at 1250 kW was installed on a peak in the Green Mountains of Vermont. The power plant was operated intermittently until 1945, when it was removed from service. The rated output of this turbine-generator was developed at wind velocities of 48 km/h or higher. Meteorologic records indicated that velocities of this magnitude could be expected to prevail for about 50 percent of the time during the year. Mechanically, a wind turbine-generator of this kind can be expected to perform satisfactorily. The feasibility of utilizing the energy in wind for power generation centers principally on the economy of the operation.

The interest in wind power generation has been revived, and numerous wind turbine-generators are now operating in the United States. While many of the units are small, the rated capability of the experimental machines extends over a wide range, up to 3 MW.

1.3 WATER POWER

Since the early colonial days, water has been used in this country, first for the production of mechanical energy and later for the generation of electric power. For many years, numerous water power plants, scattered across the nation, supplied power for the operation of small mills and factories. Eventually, a number of these installations became uneconomical to operate in competition with central stations producing electrical energy on a large scale.

Today, utility and industrial companies and governmental agencies operate water power plants that range from a low to a very high generating capability. Within the past 40 years, the federal government has undertaken the construction of several hydroelectric power plants of exceptionally high generating capability. Very often, these water power projects have multipurpose objectives, namely, power development, flood control, recreation, improvement of navigation, and irrigation of adjacent farm land.

The first water power machines were simple paddle wheels. Vanes which project into the flowing water are fastened to the periphery of a wheel that is supported on a rotating, horizontal shaft. The paddle wheel is not particularly effective because only the kinetic energy of the flowing water can be utilized in the production of power.

Erection of dams provides a means to utilizing the potential energy of stored water. Water wheels of the undershot, breast, and overshot types, all horizontal-axis machines, were installed in the low-head plants that were constructed prior to the introduction of the hydraulic turbine. These three types of water wheels differ principally in the way in which the water is admitted to the wheel. For the undershot and breast types, water is directed to the buckets on the lower portion of the wheel, while for the overshot type, water is conveyed in a flume to the top of the wheel. The conversion efficiency for a water wheel is 0.70 for an undershot-type machine and about 0.85 for the breast and overshot types.

In the United States, development of the hydraulic turbine started about 1820. The modern hydraulic turbine is a closed structure consisting of a casing in which the impeller rotates under the control of the flow regulating mechanism (Fig. 1.3). The high-capability hydraulic turbines are vertical-axis machines. Design of the turbine impeller is influenced by the operating head. Propeller-type and runners of the mixed-flow design are used in turbines installed in low-head plants. The mixed-flow design is also characteristic of the medium-head plant. Turbines installed in moderately high-head plants are equipped with runners designed for inward flow through the reaction wheel. In all of these machines, the impeller runs submerged in the casing. Conversion efficiencies are 0.90 to 0.94 for reaction-type and 0.85 to 0.93 for propeller-type turbines.[1]

The bulb-type water turbine, developed in Europe on a large scale over the past decade, is particularly effective in producing power at river sites with a high rate of flow and a head ranging up to 18 m. The bulb turbine, a horizontal-axis machine, achieves a high operating efficiency because of the straight-through flow characteristics (Fig. 1.4). In comparison with conventional machines, bulb turbines are physically smaller, a factor that causes a reduction on the order of 10 percent in the overall capital cost of a water power project.

The Pelton or impulse turbine is installed in high-head water power plants. In this design, the water is accelerated in a nozzle and directed against the buckets fastened to the periphery of a wheel that rotates on a horizontal shaft (Fig. 1.5). The pressure in the casing is essentially atmospheric; and in the vicinity of the nozzle, the casing is constructed so as to allow free discharge of the water from the buckets. The conversion efficiency for an impulse hydraulic turbine is 0.85 to 0.93.[1]

1.4 TIDAL POWER

The proposal to utilize tidal currents for large-scale power generation has, for several decades, been supported by a number of individuals who visualize an inexpensive source of electrical energy. Unlike the conventional hydroelectric power plant, constructed above sea level on a body of

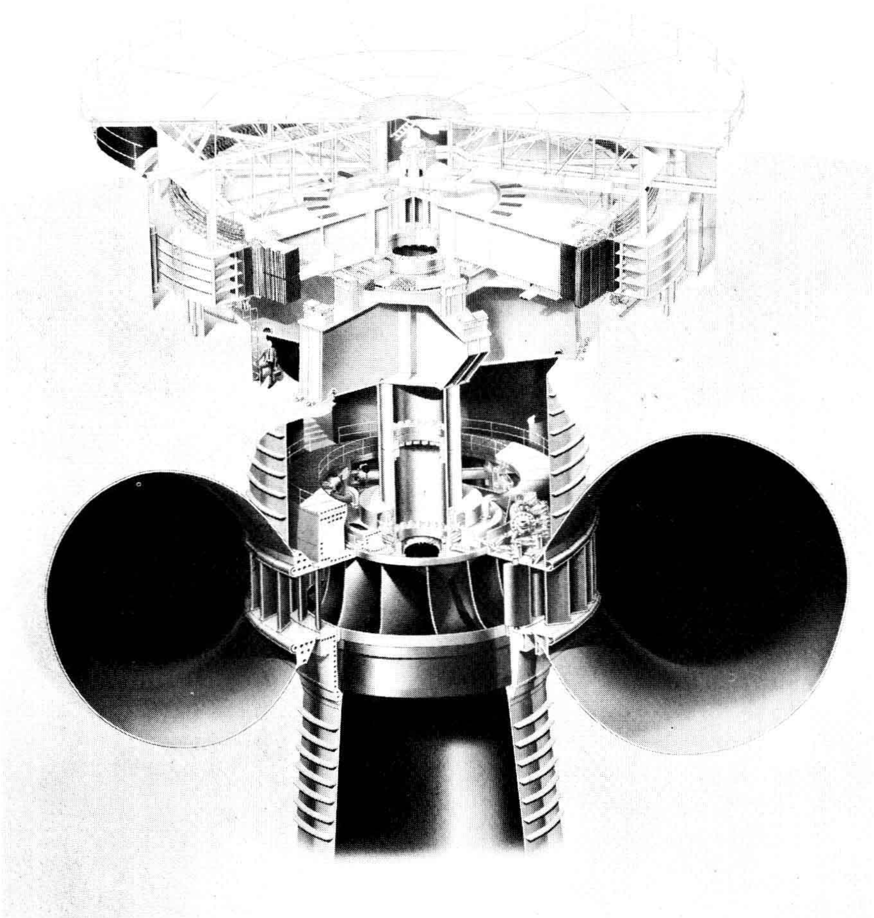

Figure 1.3 Hydraulic turbine-generator, 1000-MW class, Francis-type runner. (Photo courtesy of Allis-Chalmers Corporation.)

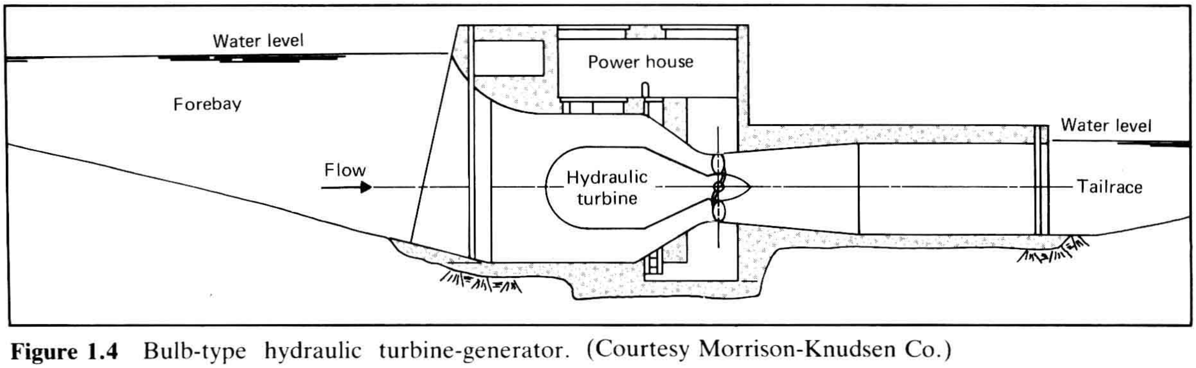

Figure 1.4 Bulb-type hydraulic turbine-generator. (Courtesy Morrison-Knudsen Co.)

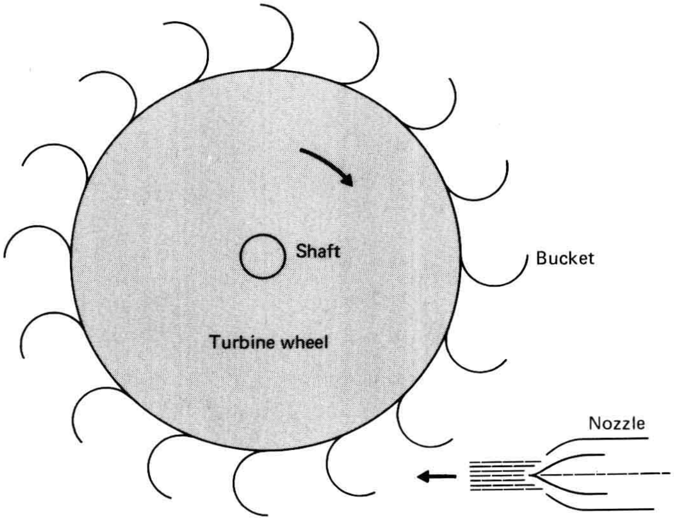

Figure 1.5 Schematic illustration of an impulse-type hydraulic turbine.

water or river, where the flow can be regulated, the tidal power plant is subjected to periods of slack water, reversed currents, and high and low water levels. Continuous output from a tidal power plant can only be achieved by providing within the system some kind of facility for storing energy.

In comparison with conventional thermal and hydro power plants, the capital cost for a tidal power plant is likely to be high, and usually most designs prove to be uneconomical. During the 1930 decade, limited backing was obtained for construction of a tidal power plant on Passamaquoddy Bay, located between Maine and New Brunswick. Some preliminary work on the project was undertaken, but the project was ultimately abandoned because of a number of objections that were raised, principally that of poor economy. In addition, the location of the power plant was remote from the probable market for the power to be produced by the plant.

The Passamaquoddy Bay power project may be revived in the light of the present endeavor to develop alternative power sources. Throughout the world, there are at least 50 other developed or potential tidal power plant sites, notably a tidal power installation in France and another in Holland that generate electrical energy on a commercial scale. Under favorable economic and technologic conditions, development of additional sites may be anticipated within the next two to three decades.

1.5 STEAM POWER

Steam, as a working substance, was introduced probably about the year 200 B.C. Several devices operated by steam were constructed, one of them the well-known reaction turbine attributed to Hero. Some of these early machines performed no useful work, while others operated simple mechanical devices that were scarcely more than novelties.

After many years of relatively unsuccessful development, the steam engine became an important source of power in the latter part of the eighteenth century. Subsequently, the steam power industry has been highly successful in maintaining a continuous program of development and expansion. The steam engine was extensively improved but was later replaced by other power machines, principally the steam turbine.

Steam-producing equipment has advanced from the simple boiler to the highly complex and very large steam generator.

The first practical "steam engine" was developed by Thomas Newcomen in 1705. Several "engines" had been built prior to the construction of Newcomen's machine, but operating difficulties precluded industrial applications. The machine developed by Newcomen was actually a steam-operated pump used for mine drainage. Flooding of the lower levels of the deep coal mines in England had by this time become a serious problem, one that required an early, economical solution. Newcomen's pump was fairly successful with respect to mechanical performance, but the operating economy was poor. The use of water jets to achieve condensation of the steam inside the cylinder caused the steam consumption to be prohibitive for many applications.

James Watt acquired a Newcomen machine in the year 1764 and began a series of experiments that 20 years later produced a steam engine capable of economical power generation. Watt and his business partner, Matthew Boulton, made many improvements on the engine, including double-acting operation, expansion of the steam in the cylinder, external condensation of the exhaust steam, and transformation of the reciprocating motion of the piston to the rotary motion of the crankshaft.

Watt and his contemporary workers, and later other investigators, further modified and improved the steam engine until it reached a high degree of mechanical perfection. The steam engine was widely used for the generation of electrical energy and as a power source for pumping water, driving machinery, propelling ships, and moving trains. Some of these engines were very large and consisted of several stages of expansion, though all turned at comparatively slow speeds. Currently, a number of investigators are engaged in the development of a steam engine suitable for application to highway vehicles.

The higher-speed steam turbine was introduced toward the end of the nineteenth century

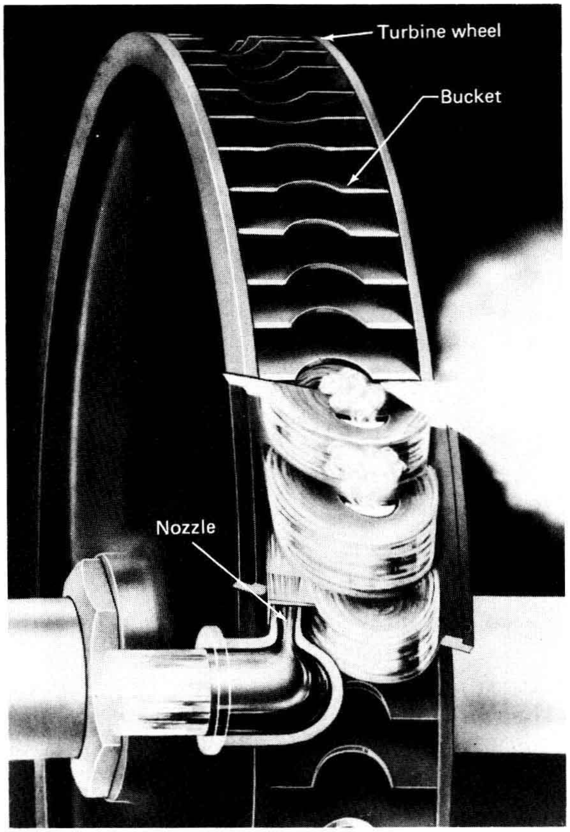

Figure 1.6 Wheel principle of the helical-flow steam turbine. (Courtesy Terry Corporation—Steam Turbine Division.)

(Fig. 1.6). The turbine, with its generally superior characteristics, soon began to replace the steam engine, particularly for driving electric generators. The turbine, similarly to the steam engine, owes its existence to the efforts of a large number of engineers. Early experimental work was started about the year 1830, but it was not until the period extending from 1880 to 1900 that a vigorous program of development was instituted.

The electric power industry originated in the small generating companies that produced electrical energy for street, home, and commercial lighting. The Pearl Street station of the New York Edison Company was the first significant central

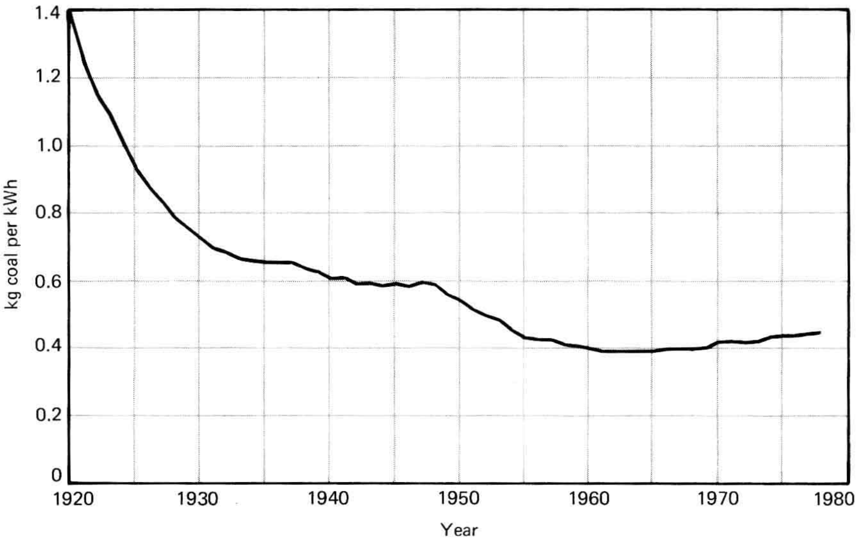

Figure 1.7 Coal rate for electric utilities in the United States. ***Source:*** Statistical Abstract of the United States, U.S. Dept. of Commerce, Bureau of the Census; and U.S. Dept. of Energy, Electric Power Statistics.

electric power plant erected in the United States. The station was constructed under the direction of Thomas Edison and began operation in the year 1882. Many new types of equipment were installed in this early power station. Subsequently, over the past 100 years, improvements in design and operating procedures have contributed to essentially a continuous increase in the thermal efficiency of the steam-electric power plant. The improved thermal performance is observed in the downward trend of the annual average coal rate for the steam-electric generating stations (Fig. 1.7).

1.6 INTERNAL COMBUSTION ENGINES

Following a number of unsuccessful experiments, the first internal combustion engine of commercial significance was constructed circa 1876. The early engines were of the flame-ignition or spark-ignition type. Development of this power plant has produced the modern lightweight, efficient "gasoline" engine that has extensive applications in the transportation field. Principal installations are in motor vehicles, aircraft, boats, light construction machinery, and miscellaneous small power plants.

Toward the end of the nineteenth century, Rudolf Diesel introduced into the power field the compression ignition internal combustion engine that subsequently became a highly important source of power. It is of interest to note that Dr. Diesel developed this engine following an unsuccessful attempt to construct an engine capable of operating on powdered coal. The modern, high-compression Diesel engine operates on a petroleum-based fuel of about the same specific gravity as kerosene. In general, the heavy, slow-speed Diesel engines are used for stationary power generation and marine propulsion. Medium- and high-speed engines are employed in motor vehicles and locomotives and in industrial machines of a great variety.

1.7 GAS TURBINE ENGINES

The first gas turbine power plant was constructed and operated in Paris in the year 1903. Owing principally to limitations imposed by the low ef-

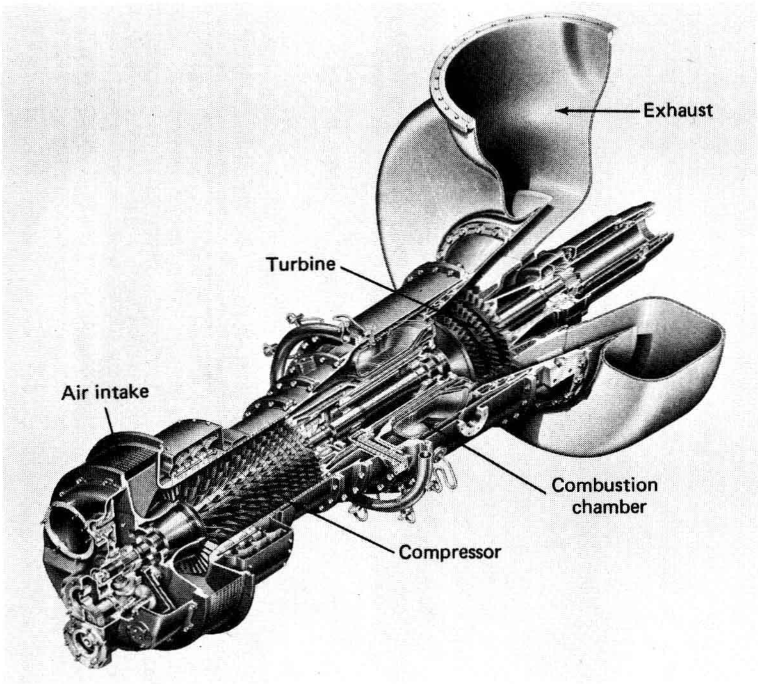

Figure 1.8 Industrial-type gas turbine engine. (Courtesy Solar Turbines Incorporated.)

ficiency of the compressor and the inability of available materials to withstand the effects of high temperature, this machine was unable to develop a useful output. As a result of technologic advances, these two principal limitations were in time largely eliminated, and the development of the gas turbine engine moved forward at a rapid pace.

The inherent characteristics of high speed and high power output promote the use of the gas turbine engine in a wide variety of applications (Fig. 1.8). Initially, the most rapid and intensive development of the gas turbine engine was in the turbojet category. The turbojet engine has replaced the reciprocating internal combustion engine for propelling large- and medium-sized aircraft. Currently, the relatively new gas turbine engine is used, in addition to propelling aircraft, to generate electrical energy, propel ships, and drive industrial machines. Contrary to the early optimistic predictions, the gas turbine engine, for a number of reasons, has not penetrated the automotive field, but investigative work in this area will continue.

1.8 NUCLEAR POWER

After fission of the uranium atom by Otto Hahn et al. (circa 1939) power generation through a controlled fission reaction was recognized as a distinct possibility. Many different investigations were required prior to the design of a nuclear power plant. Some of these studies involved the effect of radiation on the properties of structural materials, heat transfer from the reactor core, fluid flow within the core, and protection against harmful radiation.

Present-day nuclear power plants are thermal engines. Energy released in the reactor core is transferred as heat directly to the working fluid, or to an intermediate fluid and then to the working fluid. The working fluid is usually water, while liquid sodium, pressurized water, or helium gas is employed as the intermediate fluid.

Several basic designs have been proposed for the nuclear power plant. In the United States, almost all the commercial nuclear power plants are equipped with pressurized water or boiling water reactors. Water, the working fluid for both types of plants, is expanded as steam in a conventional turbine-generator.

The breeder reactor, which produces as much, or more, fuel than it consumes, has received considerable attention because of its superior fuel-burning characteristics. Adoption of the breeder reactor as a principal source of power in the United States will be dependent, in part, upon the experience derived from the operation of a demonstration plant currently in the design and early construction stage. Strong opposition to the construction of breeder-type nuclear power plants has however developed because of the high capital cost and the potential hazards that exist in the use and handling of plutonium.

1.9 ELECTRIC POWER STATIONS

Many factors are considered in planning an expansion of the generating capability of a power system. The type of power plant selected for construction should, in general, be one that produces electrical energy at a minimum cost. There are however often sound reasons for departing from this principle. Environmental constraints, an uncertain fuel supply, and probable changes occurring in the system power demand are some of the reasons that can be cited. Base load power generation is usually provided by high-capability hydroelectric and fossil-fuel and nuclear steam-electric power plants.

In the United States, most of the electrical energy is generated in steam and hydro power stations. Currently, the energy output ratio is approximately 5 to 1 for thermal and hydro power plants, respectively. As the demand for power increases, it will be necessary to construct many additional steam stations and to develop some of the remaining available water power sites. Certain of these undeveloped sites are not particularly appropriate for construction of a power plant because of the high capital cost that will result from the erection of long transmission lines, environmental restrictions, acquisition of land, and extensive construction involving the dam and the power house.

A steam power plant requires an ample supply of cooling water and adequate transportation facilities for supplying fuel. Transportation of fuel is usually achieved without major difficulty, but unrestricted use of water for thermal power plant cooling is in most locations no longer possible, hence air cooling may be required. The problems that develop with air cooling are discussed in a later chapter.

A combination of steam and hydro power plants provides an opportunity to arrange a flexible operating schedule that can improve the system performance. When the stream flow is high, more of the system load can be shifted to the hydro stations; and during periods of low runoff, the steam stations can carry a greater part of the load. In addition, the water turbine can be operated as a peak load machine, because it is readily started and stopped and there are no standby losses.

The gas turbine power plant is not, as yet, a primary power-generating unit for central station operation. In the United States, gas turbine generating sets have been installed for peaking or auxiliary service in main power plants, or enclosed in small shelters strategically located at various points in the system. The gas turbine power plant is particularly well adapted to this type of service. Delivery and erection time is comparatively short, and the machine can be started "cold" and quickly loaded. To a limited extent, the gas turbine engine has been integrated in the combined cycle with the steam power plant.

The continued increase in the demand for electric power must be met largely through expansion of steam power-generating facilities. Some